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METAL-METAL BONDLINE NDE METHODS

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The purpose of this program was the validation and refinement of an ultrasonic inspection method for examination of metal-to-metal bonds (MMB) representative of those encountered in bonded gas turbine components such as integrally-bladed rotors. The methodology was to be optimized for detection of typical defect conditions such as blown grains and microcracking. To assist in this method development, the metal-to-metal (MTM) simulation program, which was developed at Iowa State University, was to provide theoretical guidelines for method optimization.

This report is the last technical status of the program which was terminated on February 28, 1991. This report contains a review of the work completed in fabrication of bonded defect specimens, the effort in validating the MTM simulation program, and conclusions and recommendations for future similar programs.

Metal-Metal Bond Ultrasonics
Nondestructive Evaluation (NDE)
Turbine Engine, Integrally Bladed Rotors (IBR)

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Foreword

Pratt & Whitney (P&W) was contracted under Air Force contract F33615-89-5616 to conduct a research program entitled "Metal to Metal Bond Line NDE Methods" in accordance with a Statement of Work dated 22 December, 1988.

The Metal to Metal Bondline NDE program was sponsored by the U.S. Air Force Systems Command, Aeronautical Division, Wright Patterson Air Force Base, Ohio. The program was conducted by P& W's Materials Engineering organization, and the Center for Nondestructive Evaluation of Iowa State University.

This document reports on the efforts conducted during the length of the program (01 October 1989 through 28 February 1991) in accordance with Contract Data Requirement List (CDRL) Sequence No. 8.

Individuals responsible for the work of this program include:

C. Buynak	U.S. Air Force Program Manager
B. Weston	P&W Program Manager
L. Percival	Responsible Engineer
T. Gray	Principle Investigator

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1.0 INTRODUCTION

Advanced gas turbine engine concepts are continually striving toward the highest thrust to weight ratio possible. Two methods of achieving this goal are 1) higher compression ratios and 2) weight reduction through less material, lighter material or both. Development of integrally bladed rotors (IBR) is a relatively new manufacturing technique that would eliminate the need for heavier construction of the dovetail area on a rotor, while reducing gas leakage problems as well for that stage of compression. Integrally bladed rotors require reliable metal to metal bonding (MMB) techniques and the ability to adequately inspect the bond plane for defective conditions that would debit bond strength capabilities. Current ultrasonic NDE capabilities in industry allow for detection of disbond conditions, but more work is needed for detection of other defective MMB conditions. (to pg i)

The objective of the Metal-Metal Bondline NDE Methods Program was to validate and refine an ultrasonic inspection methodology for metal to metal bonds representative of those encountered in gas turbine engine components, such as integrally bladed rotors. The refinement of this methodology would be directed by results from a computer simulation model and then verified experimentally. Under previous Air Force Materials Laboratory sponsorship, the Center for Nondestructive Evaluation (CNDE) at Iowa State University (ISU) developed an analytical model of ultrasonic reflectivity from imperfect bonds based upon a quasistatic, distributed spring approximation. The effective spring constants in the model relate the change in stiffness (or compliance) at the imperfect interface to the geometrical parameters (shape and spacing) and composition (void, inclusion, or crack) of the flaws in the bond plane. The dependence of the ultrasonic reflection and transmission coefficients upon the incident angle, wave mode (longitudinal or shear), and ultrasonic frequency are predicted by the model.

This simulation model was chosen to aid Pratt and Whitney in the Metal to Metal Bondline NDE Methods Program for development of an optimum inspection methodology to detect bondline defect conditions, such as microcracking, undesirable alloy phase formation, and crystalline growth of oversize grains in the heat affected zone. For some of these types of bondlines defects, such as cracks lying in the plane of the bond, model development and experimental testing had been performed prior to startup of this program. However, the model was not capable of modeling volumetric defect conditions, such as microcracking from under temperature bonding conditions and oversized grains from over temperature bonding conditions, without software enhancement. These model developments and subsequent validation were intended to be a part of this program.

2.0 SCOPE

The scope of this program consisted of model development and validation, inspection methodology development and refinement, and sample fabrication and analysis organized into three tasks:

Task I consisted of the development of a state-of-the-art (SOA) inspection methodology, which would address the ability to detect the ultrasonic response from distributed defect conditions such as micro-cracking, oversized grains and undesirable alloy phase formation. To assist in this development, the contractor would utilize a SOA ultrasonic scattering model, which simulates the ultrasonic response from distributed defects at a bondline. This simulation model would be further enhanced to aid the contractor in the development of the inspection methodology.

Task II consisted of the fabrication and analysis of bondline defect specimens which were representative of the type found in gas turbine engine components. The specimens were to be fabricated through normal bonding conditions in a manner that would produce bonds of low quality. The defective bondline conditions would contain microcracks, oversized grains and undesirable alloy phase formation. Specimens would be fabricated from nickel-based superalloy and a titanium alloy with emphasis given to the former material type. The ratio of nickel to titanium alloy specimens would be two to one. No fewer than two thirds of the specimens were to have the shape of a typical disk bladed rotor (DBR).

Task III consisted of the experimental validation of the methodology developed in Task I on the specimens that were to be fabricated in Task II. Tests would be conducted on the specimens. Based on the results of these experimental measurements, the contractor would make changes to the methodology. A representative subset of the specimens would be metallographically sectioned and routine microscopic examination would be performed to verify the type and severity of the defective bondline conditions.

3.0 PROGRESS SUMMARY

All work has stopped in accordance with the notification for program termination. Below is a summary of all work conducted during the program period. This section will first describe the fabrication of specimens for validation of the MTM NDE simulation model. Fabrication of reliable bond plane defect conditions was necessary for accurate comparisons of experimental and simulated results. A discussion of the validation tests performed on the specimens follows, including explanations for the initial poor correlation between simulated and experimentally measured results. The remainder of the technical progress summary addresses software enhancements to the model, and a listing of all program hardware at various stages of completion before program termination. The specimens are categorized into contract deliverable and nonobligated material. The latter category is material that was acquired from surplus Pratt and Whitney inventory, and no contract funded work had yet been conducted on this material.

Validation Specimen Fabrication

Three coupons were fabricated from PWA 1074 (IN100) material for the initial model validation effort and are described as S/N 1, S/N 2 and the reference coupon. Inspection access for both longitudinal and shear mode examinations were considered when determining the coupon geometries. In agreement with ISU, a cylindrical shape was chosen instead of rectangular like previous samples. S/N 1 has a diameter of 3/4", and S/N 2 has a diameter of 5/8". This geometry allows adequate access for both longitudinal and shear components of the ultrasonic beam over a relatively large bond plane area. The bond planes are approximately 0.5 inches from flat and parallel entry surfaces of similar area. ISU originally requested a larger diameter (1.00") coupon, but the increased bond area combined with bonding equipment limitations did not produce enough pressure to bond the specimens.

S/N 1 and S/N 2 were each sprayed with stopoff, which is a yttrium oxide solution that inhibits bonding. Accurate prebond documentation of the sprayed stopoff distribution on each bond surface was obtained. Attachment 1 shows example photographs of the prebond surface of S/N 1. Automated image analysis was performed on both specimens in a randomized method to determine 1) the size (diameter) distribution for the particles and 2) the average distance between all particles. The longest dimension of the particles was set perpendicular to the machining grooves which are roughly 25 microns wide. Analysis of the surfaces were repeated to validate results and an additional background noise test was conducted to verify that accidental inclusion of machining grooves in the results was not occurring.

After prebond documentation, S/N 1 and S/N 2 were each bonded to a clean surface half. The reference sample was never bonded, a condition which simulates a perfect disbond and is necessary for calibration of the MTM model. This reference sample has similar characteristics to the bonded samples. Ideally a reference standard should be exposed to the same thermal cycle as the bonded specimens. Any grain growth and heat affected zone that occurs during bonding should be accurately represented in the reference sample. Similarly, S/N 1 and S/N 2 should be bonded with as closely matched parameters as possible, including bond cycle and material upset. By destructively analyzing one of the two samples, the internal defect condition of the remaining specimen could be more accurately assessed and modeled. S/N 1 was bonded in air to permit oxidation on the bond surfaces and allow for a clean separation of the two coupons after bonding. Although S/N 1 was bonded in air and S/N 2 was bonded in a vacuum, the joining group did not believe that this deviation in bond parameters would cause a significant difference between the two post bond stopoff patterns. This is an assumption that must be tolerated. The alternative would have been to bond S/N 1 in a vacuum, creating identical bonding conditions between the two samples, but also producing a stronger bond in S/N 1. A strong bond could prevent a clean separation of the S/N 1 halves and prohibit analysis of the postbond condition of the stopoff distribution. Attachment 2 shows example postbond photographs of the defect surface from S/N 1.

Comparison of these pre and postbond results for S/N 1 showed that the distribution of sprayed stopoff distorted during bonding. The average defect size increased by roughly 40% and the average nearest neighbor distance (center to center) between defects increased by roughly 13% percent. These results along with more detailed information was delivered to ISU and allowed for a more accurate description of the distributed defect condition in the S/N 2 bond sample.

Model Validation Tests

As a first quantitative test of the distributed spring model on bonded specimens of jet engine material, ultrasonic tests were performed on the above described validation samples. Normal incidence longitudinal wave measurements were chosen because of 1) simple specimen geometry, 2) ease of ultrasonic measurement, 3) ease of reference fabrication, requiring only a specimen of PWA 1074 of one-half the thickness of the bonded samples, and 4) model predictions which do not require knowledge of shear-mode spring constants. The latter reason refers to one of the model development, or enhancement, tasks which was undertaken in the present program, which will be described more fully below. Tests were performed using both planar, contact (20 MHz) and focused, immersion (F = 3.8", 15 MHz) transducers. Signals from the bond plane, which were easily observable, were converted to reflection coefficients by normalization with respect to the reflection from a flat, reference surface.

The reflection coefficients were simulated by assuming that the stopoff regions could be represented by penny-shaped "cracks" of size equal to that of the stopoff regions. Size distributions of the stopoff regions were prepared by P&W via microscope examination of both pre- and post-bond interfaces containing the stopoff. Microscope examination showed that the individual stopoff regions, which were applied to the pre-bond surface by atomization, appeared to be highly circular. Simulations of the reflection coefficients from the bond planes were significantly larger, on the order of +40 dB, than the experimentally measured reflectivity. Two possible explanations for this deviation are that (i.) the stopoff regions are more like flat yttria inclusions than cracks and (ii.) upset due to the bonding process caused the pre-bond surfaces to end up in intimate contact after bonding (i.e., a "kissing" bond). These results were presented at the program review meeting at the Materials Laboratory on November 29, 1990.

Model Enhancements

Model enhancements during this program consisted of development and implementation of the means for determining distributed spring constants for shear mode and for "arbitrary" bond defects (cracks, voids, inclusions of arbitrary shape). At the start of the project, the distributed spring model, as detailed by Baik and Thompson (1), had been applied to arbitrary angles of incidence and reflection relative to the bond plane (2,3). However, determination for the spring constants was limited to those for strip cracks and to the longitudinal mode constant for penny shaped cracks (1,4). For both cases, the plane of the cracks is assumed to be the bond plane. Under Air Force Materials Lab support, Rose (5,6) developed an analytical approximation for the ultrasonic reflection coefficients from a defective bond as functions of frequency and angle of incidence, for cases in which the bond plane flaws are well separated relative to the ultrasonic wavelength. This approximation requires knowledge of the far-field scattering amplitude for an individual flaw of the type found in the bond. Thus, this method can be used to determine the ultrasonic reflection coefficient whenever the scattering amplitude is known, and so can be used, in principle, for any type of flaw and for both longitudinal and shear wave modes. Some experimental tests of this approach were reported by Margetan, et al.(7).

A parallel effort, sponsored by the Industry/University Cooperative program at CNDE, was devoted to the development of boundary element solutions for scattering amplitudes for irregular shaped flaws (8). In that work, the flaws could be modeled as voids, cracks or inclusions and scattering amplitudes could be calculated for both longitudinal and shear wave modes in arbitrary angles of incidence with respect to the flaw. In the present program, Rose's single scattering theory for reflection coefficients was coupled with the boundary element

capability to create the ability to calculate arbitrary mode reflection coefficients from a variety of bond flaws. These reflection coefficients are linearly related to the desired effective spring constants for the distributed spring model, (see the Appendix to reference 4, e.g.), which provides a way to calculate or tabulate those constants.

Additional Fabricated Hardware

In addition to the three validation specimens descibed at the beginning of this section, other specimens were to be fabricated and are at various stages of completion. These specimens are listed below and on Table #1. Note that some of the specimens are unworked materials that were surplus inventory before the MTM program began. These specimens are not considered contract deliverables.

Contract deliverable material

- (8) PWA 1074 (Ni) blade blocks machined from pancake
  dimensions are 2.5″ X 1.69″ X 0.44″
- (17) PWA 1227 (Ti) cylinders
  dimensions of 1.00″ Diameter X 1.90″ axial length
- (1) PWA 1227 (Ti) blade block material
  dimensions of 1.90″ X 4.00″ X 1.00″
- (1) PWA 1227 (Ti) blade block material
  dimensions of 1.90″ X 4.50″ X 0.59″
- (3) PWA 1227 (Ti) blade block material
  dimensions of 1.90″ X 5.50″ X 0.59″
- (1) PWA 1227 (Ti) subdiameter rotor with blade stubs
- (35) PWA 1227 (Ti) blocks
  dimensions of 1.25″ X 1.75″ X 0.25″

Nonobligated contract material

These specimens were acquired from surplus inventory at Pratt and Whitney. Because no contract funded work had been conducted yet on these specimens, they are not considered deliverable items.

- (4) PWA 1074 (Ni) airfoils with blown grain conditions
- (15) PWA 1074 (Ni) airfoils with no defects
- (1) PWA 1074 (Ni) subdiameter rotor with blade stubs
- (4) PWA 1227 (Ti) airfoils with no defects

TABLE 1

MTM PWA 1074 (Nickel Alloy) COUPONS
CONTRACT DELIVERABLE MATERIAL

S/N	DEFECT TYPE	UPSET	DURATION & TEMPERATURE
10	Microcracks	0.060″	00:07:00 from 1700F to 1800F
11	Microcracks	0.072″	00:07:25 from 1700F to 1800F
12	Microcracks	0.067″	00:07:40 from 1700F to 1824F
13	Microcracks	0.070″	00:06:10 from 1700F to 1804F
14	Microcracks	0.070″	00:06:40 from 1700F to 1801F
16	Microvoids	N/A 0.124″	03:05:00 from 2217F to 2201F 00:18:20 from 1800F to 2000F
Note:	S/N 16 was fabricated with a two step process		
17	Microvoids	N/A 0.107″	02:36:00 from 2217F to 2199F 00:12:50 from 1800F to 2000F
Note:	S/N 17 was fabricated with a two step process		
18	Microvoids	0.055″	00:09:30 from 1800F to 1950F
Note:	Before the above process was performed, half of S/N 18 was untreated PWA 1074, the other half of the bond coupon was pre-processed with the following parameters:		
	Microvoids	N/A	02:36:00 from 2221F to 2210F
19	Microvoids	0.150″	00:13:45 from 1800F to 1970F
Note:	Before the above process was performed, half of S/N 19 was untreated PWA 1074, the other half of the bond coupon was pre-processed with the following parameters:		
	Microvoids	N/A	03:05:00 from 2210F to 2198F

The above parameters are the measurements documented during bonding. The objectives that were originally targeted to fabricate the desired defect conditions are listed below.

Microvoids: Hold temperature at 2225F for approximately 4 hours. Specimens showed minimal upset, consequently, no bond occured. Specimens were cleaned upo, filed down and bond interface ground smooth. Specimens were then bonded at 1875F with 0.100″ upset at 20 KSI.

Microcracks: Hold load to 20 KSI, heat to 1800F, upset 0.070 and then turn power off.

4.0 CONCLUSIONS AND RECOMMENDATIONS

The previous sections in this report first describe the fabrication of three simulation model validation specimens. Methods and limitations in documenting the bondline defect distributions were also addressed. Then a description of the validation tests that were conducted at ISU follow. These tests were to determine the accuracy of the model in predicting quantitative measurements of the ultrasonic reflection from a defective bondline, assuming that an accurate representation of the defect distribution was known and modeled. Pratt and Whitney's position was that the model must be proven before used to direct program efforts in determining an optimum ultrasonic methodology for bondline defect detection. The results of this validation study showed that the simulation model predicted amplitudes that were 40 dB greater than experimentally measured values. One explanation for the poor correlation is that the yttria stopoff solution behaves ultrasonically like an inclusion rather than a planar crack. If so, this difference in condition could explain at least a portion (unquantified) of the 40 dB disparity between simulated and experimental results. Metallography has not yet been performed on the specimens. Despite the above uncertainties, the initial correlation of simulated and experimental results was discouraging and the program was terminated.

The following text provides a discussion of knowledge learned in the MTM program, and recommendations to consider should a similar program be funded in the future.

<u>MTM NDE Model Enhancements</u>

At the present time, the MTM NDE model is limited in the type of defect conditions that may be modeled, and requires additional development to provide a tool in assisting industry in determining an optimum ultrasonic methodology for bondline defect detection. These enhancements would focus on modeling more realistic defect conditions (e.g. blown grains, porosity, microcracking as volumetric conditions); currently the model can consider only defect conditions in a plane. Other areas for enhancement would address ultrasonic beam propagation, attenuation and noise in typical metals used in diffusion bonding, calibration methods, and analytical models to account for component geometry.

<u>Bonding Technology</u>

Discussions were held with the Joining Group in the Materials Lab to determine what defect conditions are most likely to occur in typical industrial diffusion bonding practices. Any future program that is initiated may want to focus funding and efforts in developing optimum ultrasonic methodologies for one or two defect types. Of most concern in the Materials Lab are 1) oversized crystalline grains from overtemperature bonding conditions and 2) surface contamination. These two defective bond conditions are also the easiest to fabricate, but ultrasonic detection of the latter defect type, contaminates, wh[illegible] are very small inclusions in the bond plane, is a very difficult task. It was decided that fo[illegible] program, contamination would not be addressed and that efforts would be concentrated in detection of blown grains and one additional defective condition, selected from the following list of other, less likely defect conditions that could occur during diffusion bonding.

1) Micro-cracking is produced from low temperature bonding conditions.

2) Undesirable phase formation is a condition for which no reliable method of producing had yet been determined in this program. This condition is a low priority concern in the Joining Group.

3) Oxidation of bond surfaces from off-gasing during bonding of adjacent surfaces.

4) Porosity occurs from overtemperature bonding conditions and is associated with blown grains.

After reviewing the above choices, blown grains and microcracking were chosen as the defective conditions that would be evaluated in this program. These defect conditions are relatively easy to fabricate and are a genuine concern for the Materials Lab Joining Group during diffusion bonding procedures.

Reliable Defect Fabrication/Documentation

At the beginning of this program, sprayed stopoff was the only defect condition that could be accurately measured and reliably produced. The yttria solution was used to fabricate the validation specimens described in section 3.0. If future enhancements in defect modeling are to be conducted on the MTM NDE simulation model, or any other similar model, then concurrent bonding technology development would be necessary to demonstrate reliable fabrication and documentation of realistic defect conditions, such as blown grains and microcracking, to permit accurate validation of those model enhancements.

Experimental Methods

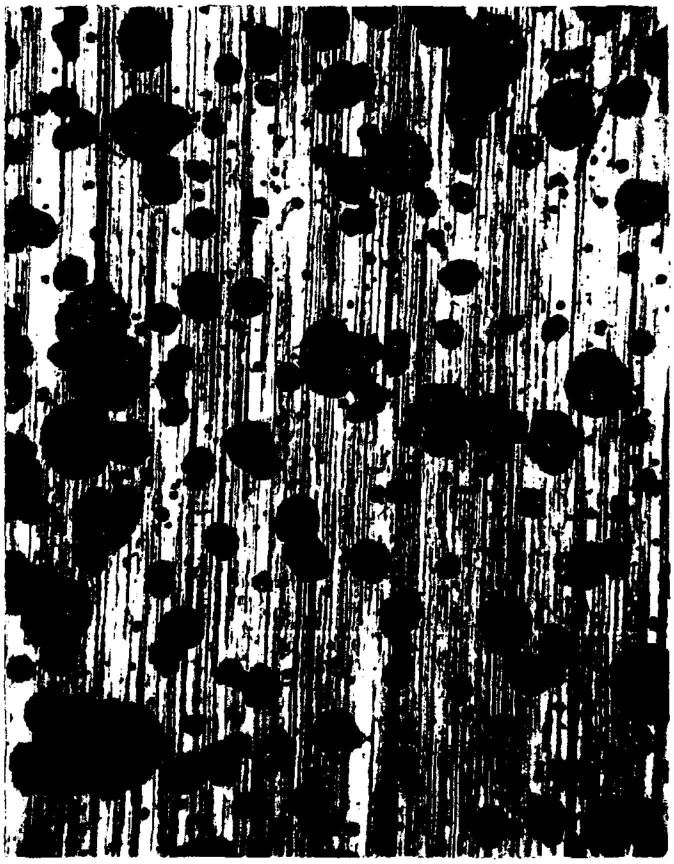
Future emphasis toward determination of an optimum ultrasonic methodology for bondline defect detection should also consider experimental approaches, independent of the availability of models for particular bondline defect conditions.

ATTACHMENT 1

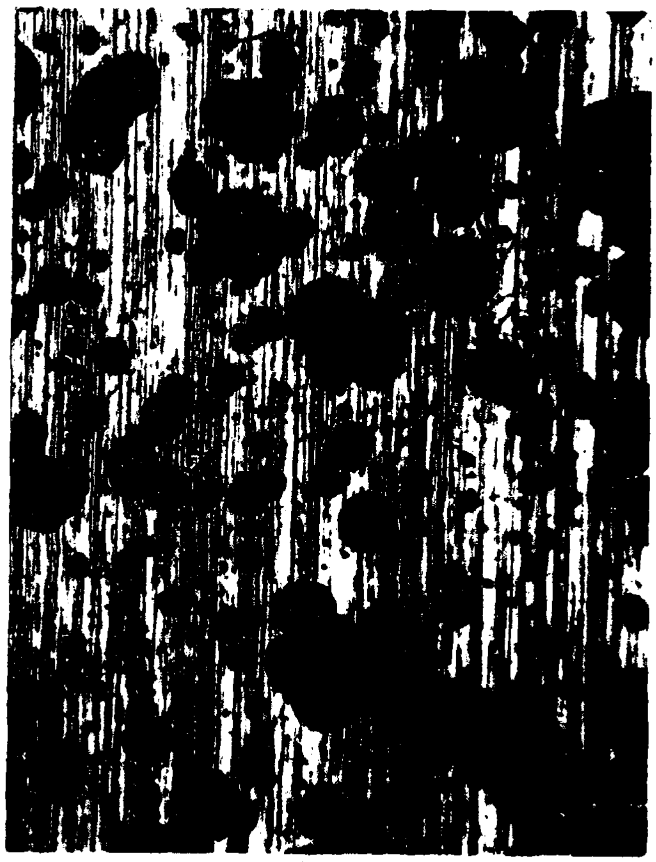
EXAMPLE PHOTOGRAPHS OF STOP OFF DISTRIBUTION ON SERIAL NUMBER 1 COUPON

(PREBOND CONDITION)

100X MAGNIFICATION
PWA 1074 (NI) MATERIAL



(a)



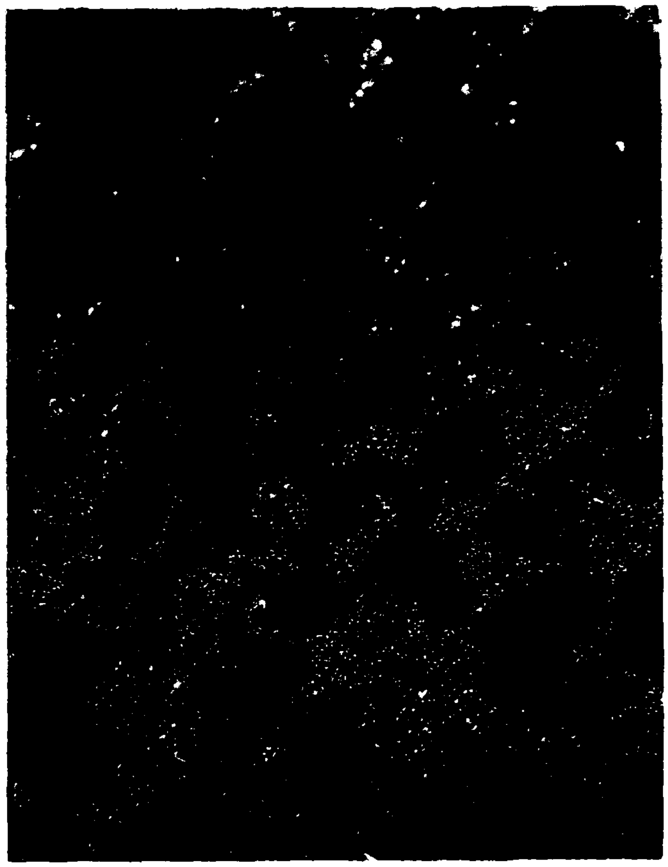
(b)

EXAMPLE PHOTOGRAPHS OF STOP OFF DISTRIBUTION
ON SERIAL NUMBER 1 COUPON

(POST BOND CONDITION)

100X MAGNIFICATION
PWA 1074 (NI) MATERIAL

(a)



(b)

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